

Phenomenology of $U(1)'$ -extended MSSM

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Class talk in PH835 (Fall 2004)

Outline

- 1. MSSM and its limit
- 2. $U(1)'$ -extended MSSM
- 3. TeV-scale $U(1)'$ gauge boson (Z')
- 4. Implications of $U(1)'$ -extended MSSM
- 5. Summary and Outlooks



1. MSSM and its limit

MSSM (Minimal Supersymmetric SM)

- Minimal : Minimal number of fields and symmetry
 1. Minimal gauge group
: SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$
 2. Minimal field contents
: (SM fields + 1 extra Higgs doublet) & Superpartners
 3. Soft breaking terms
: to break Supersymmetry
 4. R-parity
: to avoid fast proton-decay
- Besides SUSY and its breaking terms, the only additions in the MSSM are an extra Higgs doublet and R-parity.
- Question : Is it adequately minimal? (maybe too minimal?)

μ -problem of the MSSM

- MSSM superpotential :

$$W_{\text{MSSM}} = \lambda_E L H_2 E^C + \lambda_D Q H_2 D^C + \lambda_U Q H_1 U^C + \mu H_1 H_2$$

(μ : the only dimensionful parameter in SUSY-conserving sector in the MSSM)

- Quadratic scalar potential :

$$V_{(2)} = \mu^2 (|H_1^0|^2 + |H_2^0|^2) + (\text{EW/TeV-scale SUSY-breaking terms})$$

To have Higgs VEV $\approx O(\text{EW})$, μ should be also $\approx O(\text{EW})$ to avoid fine-tuning.

- Why SUSY-conserving parameter (μ) scale \approx SUSY-breaking parameter (soft terms) scale? (the μ -problem : fine-tuning problem of MSSM)

Other issues in the MSSM (cosmology related)

- To have a sufficient first-order phase transition for the EWBG(Electroweak Baryogenesis), m_h should be only slightly above the LEP limit and $m_{\text{stop}} < m_{\text{top}}$. (fine-tuning in the parameter space of MSSM)
- In the CMSSM(Constrained MSSM) with mass unification assumptions at GUT scale, the parameter space that can reproduce the acceptable CDM relic density is becoming increasingly narrow when combined with the LEP constraints (Higgs mass, chargino mass, ...). (fine-tuning in the parameter space of CMSSM)
- The issues in the MSSM suggests :
Even if nature holds Supersymmetry at TeV-scale, the MSSM may not fully describe the TeV-scale physics.


What is next?

Model	SM	MSSM
Fine-tuning problem	gauge hierarchy problem	μ -problem
Cure	Supersymmetry	What (symmetry)?

- What (symmetry) would be cure of the fine-tuning in the MSSM?
- And what would be the naturally extended model of the MSSM that can suitably describe TeV-scale physics?

NMSSM (Next-to-Minimal Supersymmetric SM)

- Extension of MSSM with a discrete symmetry [Z_3] and a Higgs singlet (S)
- Superpotential for the Higgs sector in NMSSM :
$$W_{\text{NMSSM}} = \lambda S H_1 H_2 + (\kappa/3) S^3$$
- $\mu H_1 H_2$ is prohibited by a discrete Z_3 symmetry and μ -term is replaced by the VEV of the singlet $\mu_{\text{eff}} = \lambda \langle S \rangle$
→ no μ -problem.
- Acceptable level of Baryogenesis can be achieved.


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- But, the discrete symmetry predicts cosmological domain walls which are not observed (domain wall problem of NMSSM).
 - However, there is a variant of the NMSSM (nMSSM) that can avoid the domain wall problem.



2. $U(1)'$ -extended MSSM

U(1)'-extended MSSM

- Extension of MSSM with an Abelian symmetry [U(1)'] and a Higgs singlet (S)
- Superpotential for the Higgs sector [for one singlet model] :
$$W_{U(1)'\text{-MSSM}} = h_S S H_1 H_2$$
- Instead of a discrete symmetry (of NMSSM), an Abelian gauge symmetry U(1)' is introduced → no domain wall problem.
- $\mu H_1 H_2$ is prohibited by the U(1)' charge assignment and μ -term is replaced by the VEV of the singlet $\mu_{\text{eff}} = h_S \langle S \rangle$
→ no μ -problem
(for example, $Q'(H_1) = Q'(H_2) = -1, Q'(S) = 2$)

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- The Higgs singlet S is charged under only $U(1)'$ and is responsible to break the $U(1)'$ spontaneously at the EW/TeV-scale (to provide EW-scale μ -term for reasonable values of h_S).
 - It naturally predicts a EW/TeV-scale Z' gauge boson :

$$M_{Z'} = g_{Z'} [Q'(H_1) v_1^2 + Q'(H_2) v_2^2 + Q'(S)^2 s^2]^{1/2}$$


$$\sim g_{Z'} Q'(S) s \sim O(\text{EW/TeV})$$

Sources of $U(1)'$

- $U(1)'$ -extended MSSM is a natural extension of the MSSM since ,besides the bottom-up reasons, many new physics models predict extra $U(1)$ symmetries or Gauge bosons :
 1. Grand Unified Theory (GUT)
 2. Extra dimension
 3. Superstring
 4. Dynamical EW symmetry breaking
 5. Little Higgs
 6. Stueckelberg mechanism

Extended/Modified particle spectrum

- (1) Gauge boson sector (Z') :
It may affect Z boson through Z - Z' mixing. If Z' coupling is family non-universal, FCNC (Flavor Changing Neutral Current) by Z' occurs at the tree-level.
- (2) Higgs sector (S) :
The mixing of Higgs doublets and singlet \rightarrow The LEP limit of SM-like Higgs mass ($m_h > 115$ GeV) does not apply. (A lighter Higgs is allowed.)

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- (3) Neutralino sector (Z' -ino, singlino) :
It is extended to 6-components [MSSM: 4, NMSSM: 5] and has significant effect in the cold dark matter property (the mass and the coupling of the lightest neutralino is altered).
 - (4) Neutrino sector :
Neutrino may be Dirac if ν_R has $U(1)'$ charge [still Majorana if its $U(1)'$ charge is 0].
 - We will discuss specific phenomenology of these modified sectors in “Section 4. Implications of $U(1)'$ -extended MSSM”.

Multiple singlets $U(1)'$ model [S-model]

- Superpotential for the Higgs sector in the S-model [multiple singlets model] : [Erler, Langacker, Li \[PRD66 \(2002\) 015002\]](#)

$$W_{\text{S-model}} = h_S S H_1 H_2 + \lambda_S S_1 S_2 S_3$$

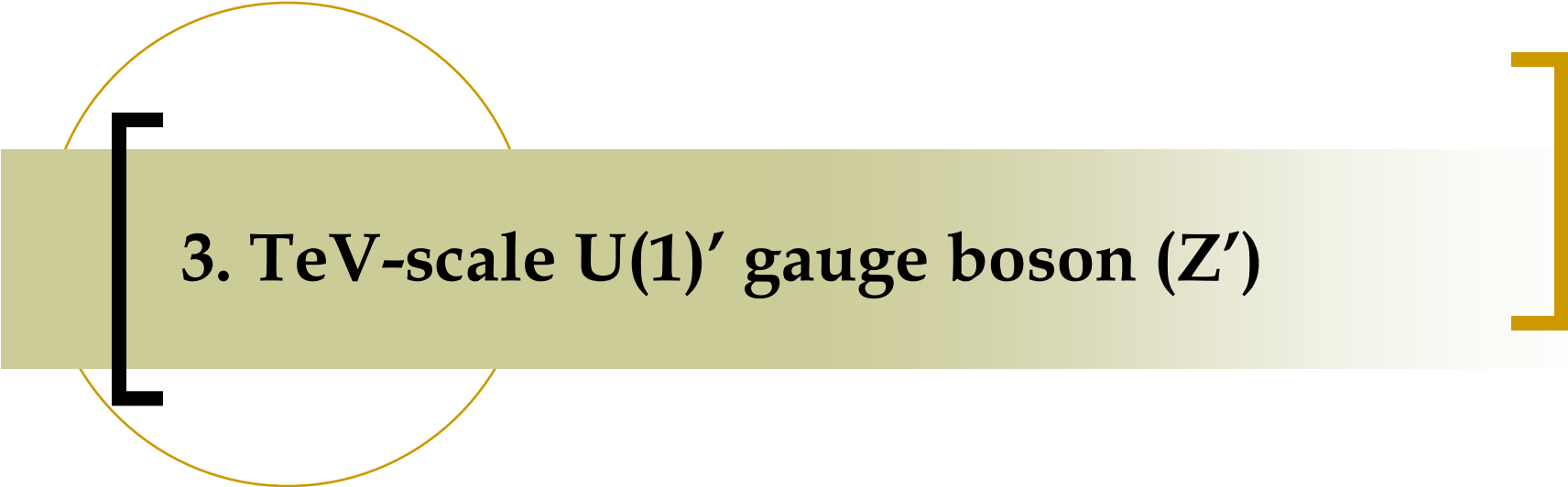
- Interesting features of the S-model :
 - Small $\tan\beta$ ($= 1 \sim 3$) to be consistent with the EW symmetry breaking
 - Provides acceptable level of EWBG.
[Kang, Langacker, Li, Liu \[hep-ph/0402086\]](#)

- Can have Z' heavy enough (TeV-scale) for any experimental constraints (including future limits) easily while keeping μ_{eff} in EW scale.

$$M_{Z'} = g_{Z'} [Q'(H_1)^2 v_1^2 + Q'(H_2)^2 v_2^2 + Q'(S)^2 s^2 + \sum_{i=1 \sim 3} Q'(S_i)^2 s_i^2]^{1/2}$$

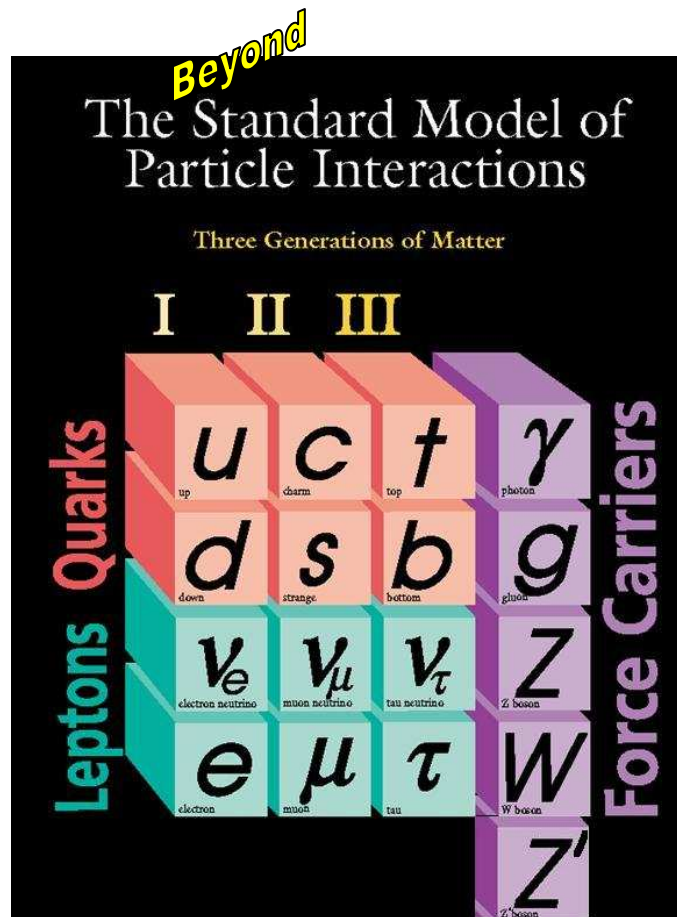
$$\mu_{\text{eff}} = h_S \langle S \rangle$$

(Note additional contributions from $\langle S_{1,2,3} \rangle$ to $M_{Z'}$ only.)



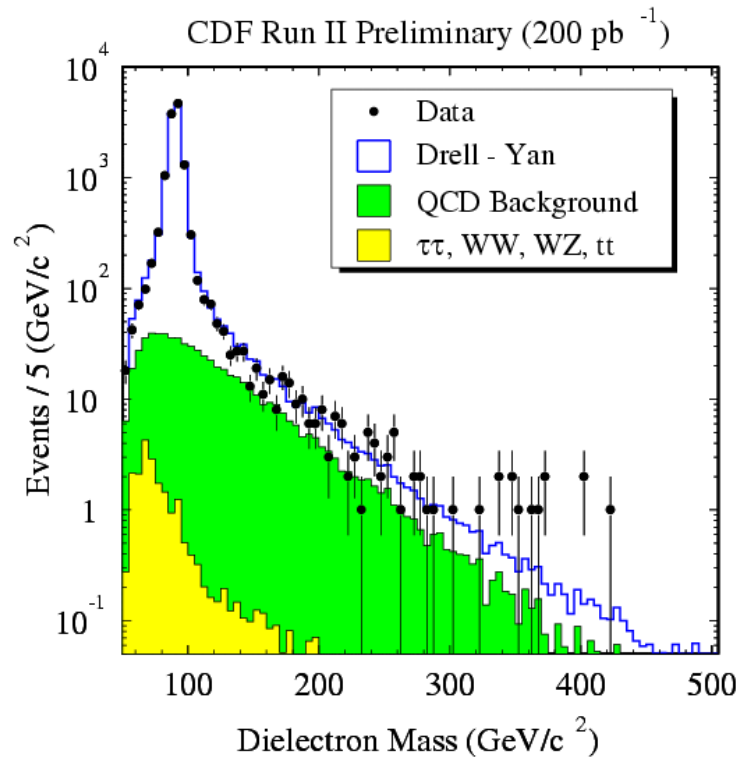
3. TeV-scale $U(1)'$ gauge boson (Z')

New force carrier



- $U(1)'$ is the new force and it needs a new force carrier (Z').
- The $U(1)'$ -extended MSSM predicts the Z' with EW/TeV-scale mass because it is correlated to the μ_{eff} which should be $O(\text{EW})$.

Resonance by Z'



CDF Run2 Preliminary
[FermilabToday (Feb '04)]

- The direct detection of Z' can be achieved by observation of the resonance in dilepton (dilepton or dijet) channels.

- Though deviation from the SM was not observed, the uncertainty around 300 - 400 GeV keeps the possibility of potential discovery of Z' resonance in the future. (More data are anticipated to reduce the errors.)

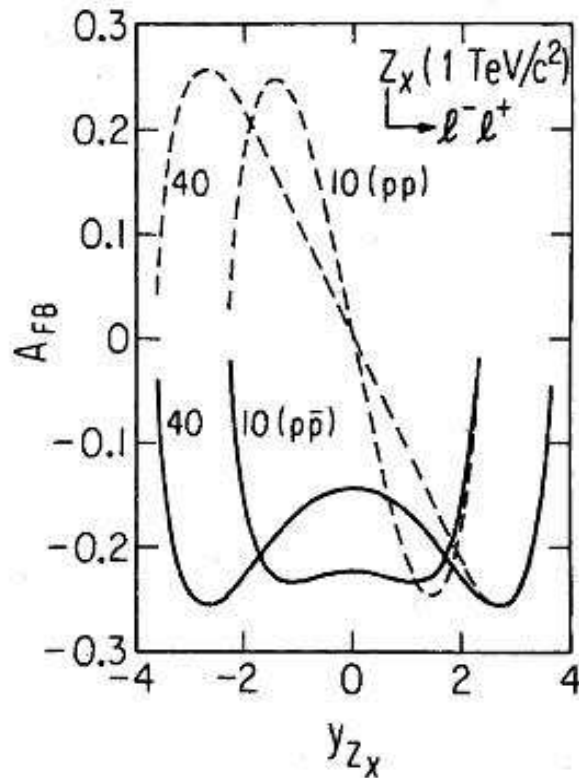
CDF Z' mass limits from dilepton search

Model	E ₉ Mass Limit at 95% C.L (GeV/c ²)		
	e^+e^-	$\mu^+\mu^-$	$\ell^+\ell^-$
Z'_{SM}	750	735	815
Z'_ψ	635	600	690
Z'_χ	620	585	670
Z'_η	655	640	715
Z'_1	575	540	610

CDF Run2A result
[Workshop on Z's (Nov '04)]

- The current limits of Z' mass are (500 – 800) GeV depending on models.
- Resonance is one of cleanest signal.
- The LHC reach of Z' would be 2 TeV at day 1; it can search up to 5 TeV.

Distinguishing models



- Forward-Backward asymmetry contains information of the charge assignments.
- It is useful in identifying gauge bosons (e.g., among E_6 models)

• A_{FB} in $pp \rightarrow Z' \rightarrow l-l^+$ with rapidity

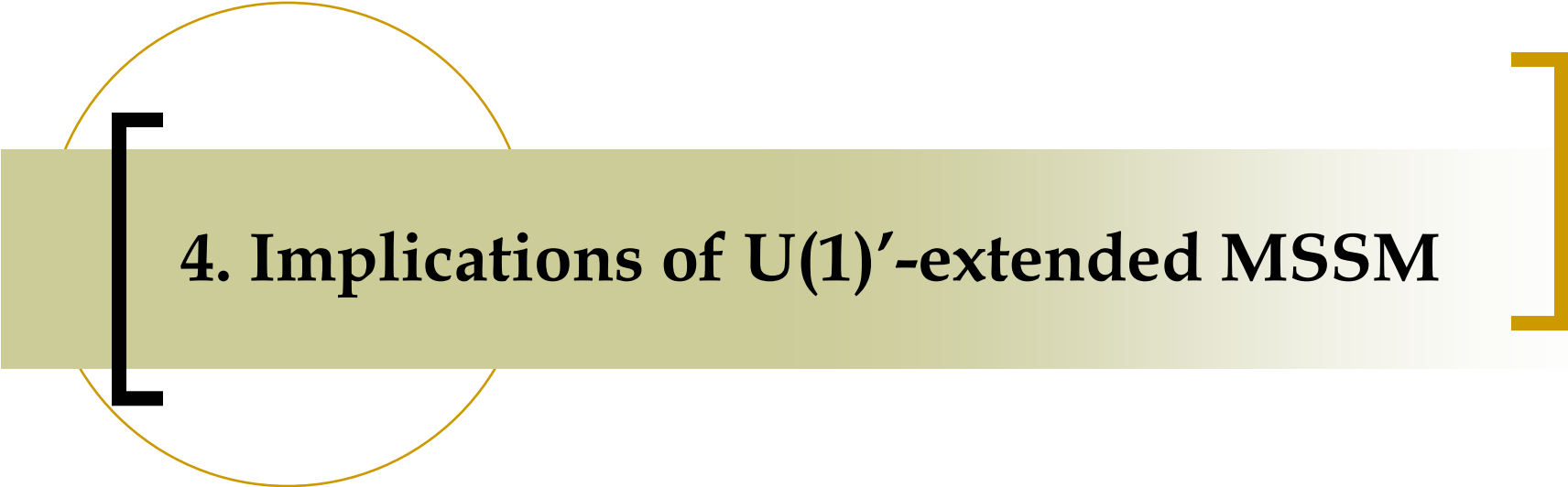
Langacker, Robinett, Rosner
[PRD30 (1984) 1470]

Other possible sources of resonance (Z' -like signals)

- Observing the resonance does not necessarily mean the existence of additional $U(1)$ symmetry.
 1. Part of non-Abelian gauge symmetry such as the 3rd component of $SU(2)_R$.
 2. Kaluza-Klein excitations in extra dimension
 3. String resonance
- Distinguishing the source of the resonance is important.

Z-Z' mixing

- $Z_1 = Z_{\text{SM}} \cos\delta + Z' \sin\delta$
- $Z_2 = -Z_{\text{SM}} \sin\delta + Z' \cos\delta$
- $\tan^2\delta = (M_{\text{SM}}^2 - M_{Z_1}^2) / (M_{Z_2}^2 - M_{\text{SM}}^2)$: mixing angle of Z-Z'
- LEP results : $\delta < (\text{a few}) \times 10^{-3}$
- Why so small mixing?
 - This is a natural value for sufficiently heavy Z'
(about current experimental limit of 500 ~ 800 GeV or heavier)



4. Implications of $U(1)'$ -extended MSSM

- (1) Higgs sector
- (2) Neutrino sector
- (3) Neutralino sector
- (4) Gauge boson sector

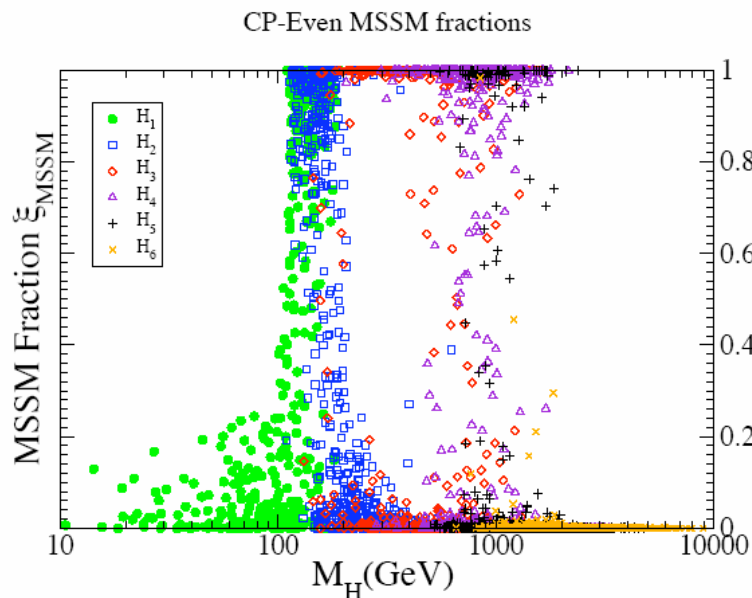
(1) Higgs sector

- Higgs sector (S) :

The mixing of Higgs doublets and singlet → The LEP limit of SM-like Higgs mass ($m_h > 115 \text{ GeV}$) does not apply. (A lighter Higgs is allowed.)

- (i) Modified Higgs mass and coupling

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Han, Langacker, McElrath
[hep-ph/0405244]

- The mixing of Higgs doublets and singlet
→ The light Higgs can be significantly smaller than the LEP limit of SM-like Higgs mass ($m_h > 115$ GeV) because singlet does not interact with other SM particles.
- Be prepared to have a Higgs as light as only 10 GeV without conflict with LEP constraints.

(2) Neutrino sector

- Neutrino sector :

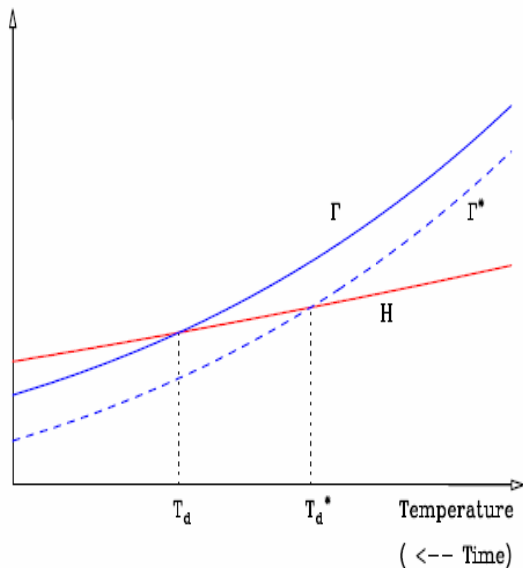
Neutrino may be Dirac if ν_R has $U(1)'$ charge [still Majorana if its $U(1)'$ charge is 0].

- (i) Neutrinoless double beta decay
- (ii) Big Bang Nucleosynthesis (BBN) constraint on Z'

(i) Neutrinoless double beta decay ($0\nu\beta\beta$)

- If $0\nu\beta\beta$ is observed, it will tell neutrino is Majorana.
→ ν_R must have 0 charge.
- Keep open mind that neutrino may be Dirac and $0\nu\beta\beta$ may never be observed, where alternatives to the see-saw mechanism may be important (TeV-scale seesaw, extra dimension, high-dimensional operator etc.)

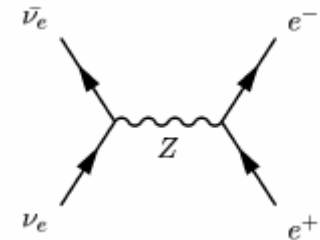
(ii) Big Bang Nucleosynthesis constraint on Z'



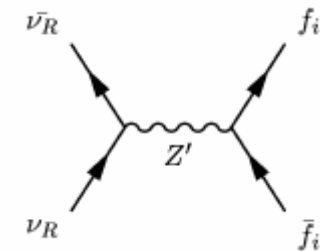
$\Gamma(T)$: interaction rate of particle A
 $H(T)$: cosmological expansion rate

- For $\Gamma > H$, particle A is in equilibrium
- For $\Gamma < H$, particle A is decoupled.
- Decoupling temperature of particle A, T_d is where $\Gamma(T_d) = H(T_d)$.
- T_d carries information about interaction of particle A.

- For SM neutrino of mass ≈ 0 :
- $\Gamma(T) \equiv n \langle \sigma v \rangle \approx 1/4 G_W^2 T^5$
- $G_W \propto g_Z^2/M_Z^2$: weak coupling constant

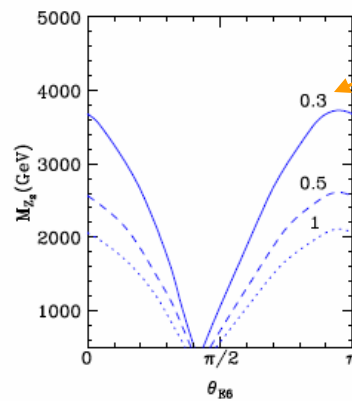
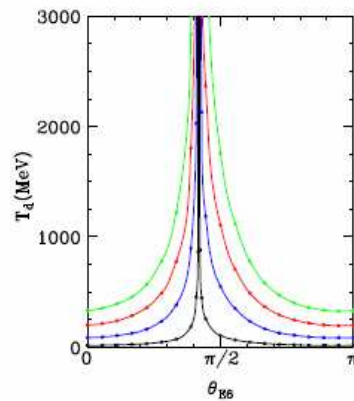


- For ν_R (couples only to Z') of mass ≈ 0 :
- $G_{SW} \propto g_{Z'}^2/M_{Z'}^2$: super-weak coupling constant
- $G_{SW} \ll G_W$ (because of $M_{Z'} \gg M_Z$)
- \rightarrow smaller $\Gamma(T) \rightarrow$ earlier decoupling (high T_d)



- $M_{Z'} \leftrightarrow T_d(\nu_R)$ from above (*higher T_d for larger $M_{Z'}$*)
- $T_d(\nu_R) \leftrightarrow \Delta Y$ (^4He abundance discrepancy) from BBN and entropy conservation (*smaller ΔY for higher T_d*)

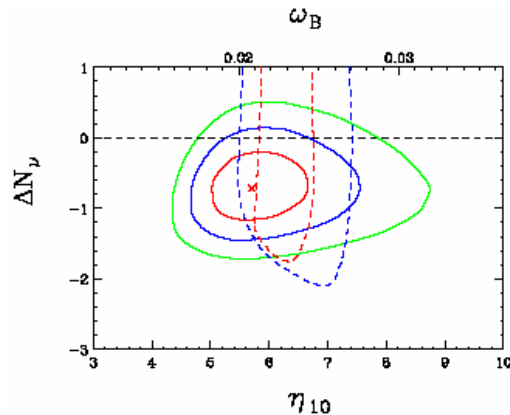
Steigman, Olive, Schramm
[PRL43 (1979) 239]



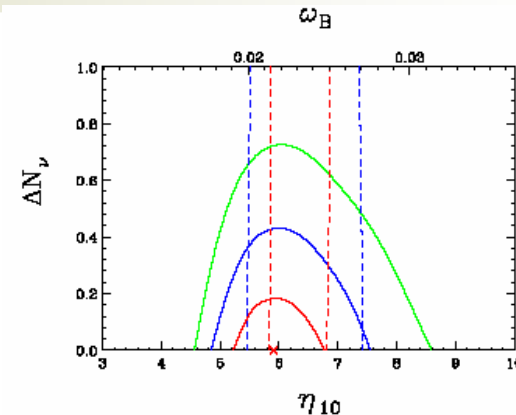
Barger, Langacker, HL
[PRD67 (2003) 075009]

- For $M_{Z'} = 0.5, 1.5, 2.5, 3.5$ TeV.
- At θ_{E6} (mixing angle of 2 $U(1)'$ in E_6 model) $= 0.42 \pi$, $Q'(v_R) = 0$ (v_R does not couple to Z').
- If observed ^4He abundance (ΔY) from BBN is due to Z' , it gives *the most stringent constraint* on Z' mass unless v_R 's are not coupled to Z' (Mostly, $M_{Z'} > \text{multi-TeV}$).

Observed ΔN_ν (effective neutrino number) from BBN(+WMAP)



	N_ν (2σ range)	η_{10} (2σ range)
WMAP	0.9 – 8.3	5.58 – 7.26
$y_D + Y(\text{OSW})$	1.7 – 3.0	4.84 – 7.11
$y_D + Y(\text{IT})$	2.4 – 3.0	5.06 – 7.33
WMAP + $y_D + Y(\text{OSW})$	1.7 – 3.0	5.53 – 6.76
WMAP + $y_D + Y(\text{IT})$	2.4 – 3.0	5.58 – 6.71



	N_ν (2σ bound)	η_{10} (2σ range)
WMAP	8.3	5.64 – 7.30
$y_D + Y(\text{OSW})$	3.3	5.04 – 7.18
$y_D + Y(\text{IT})$	3.1	4.89 – 6.56
WMAP + $y_D + Y(\text{OSW})$	3.3	5.66 – 6.80
WMAP + $y_D + Y(\text{IT})$	3.1	5.54 – 6.60

Barger, Kneller, HL, Marfatia, Steigman [PLB566 (2003) 8]

WMAP is not very good in constraining ΔN_ν (though it is good for Baryon asymmetry η_{10}).

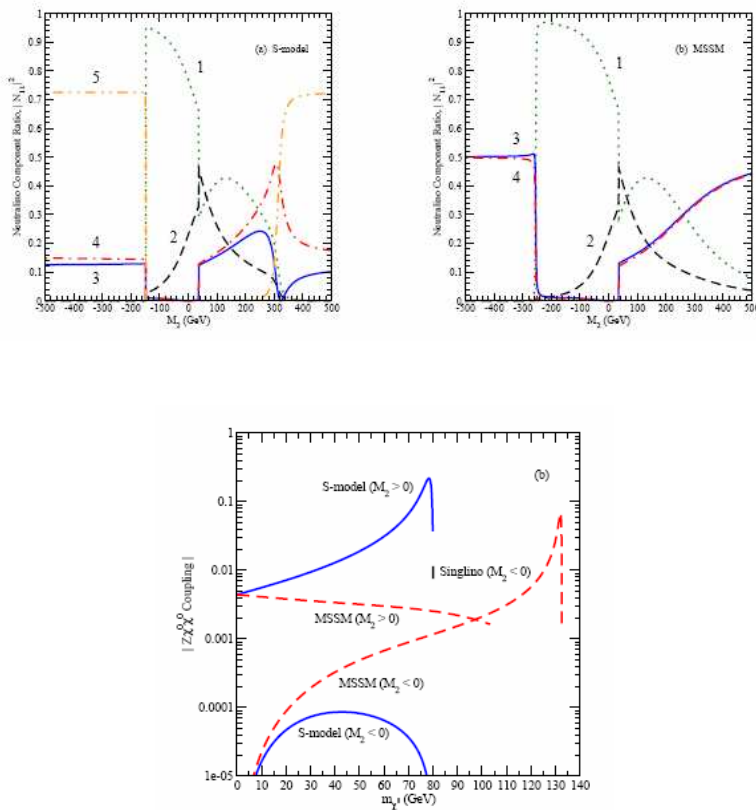
From BBN(+WMAP) $\Delta N_\nu \leq 0.0$ or 0.3 (with $N \geq 3$ condition)

(3) Neutralino sector

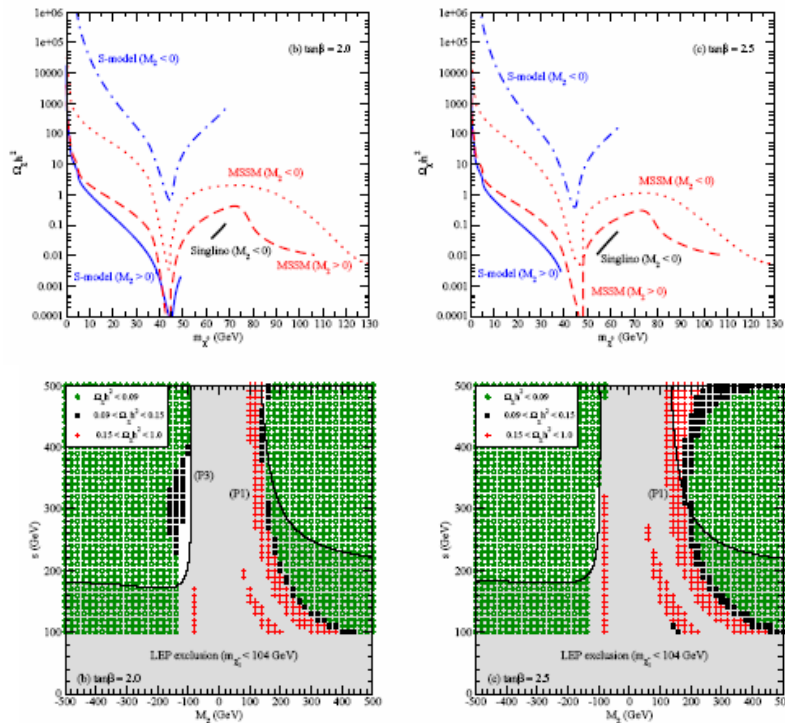
- Neutralino sector (Z' -ino, singlino) :
It is extended to 6-components [MSSM: 4, NMSSM: 5] and has significant effect in the cold dark matter property (the mass and the coupling of the lightest neutralino is altered).
- (i) CDM relic density
- (ii) CDM direct detection
- (iii) Muon anomalous magnetic moment $(g-2)_\mu$

(i) CDM relic density

- WMAP precise measurement of cold dark matter relic density : $0.09 < \Omega_{\text{CDM}} h^2 < 0.15$
- The lightest neutralino (χ^0_1), the lightest supersymmetric particle is a strong candidate for CDM.
- The modified neutralino sector is extended to $\chi^0 = \{\text{B-ino}, \text{W-ino}, \text{Higgsino}_1, \text{Higgsino}_2, \text{Z'-ino}, \text{Singlino}\}$ and the LSP is often Singlino-like and its mass bound is smaller than that of MSSM.
(for example, mass of $\chi^0_1 < 100$ GeV for large Z'-ino mass)



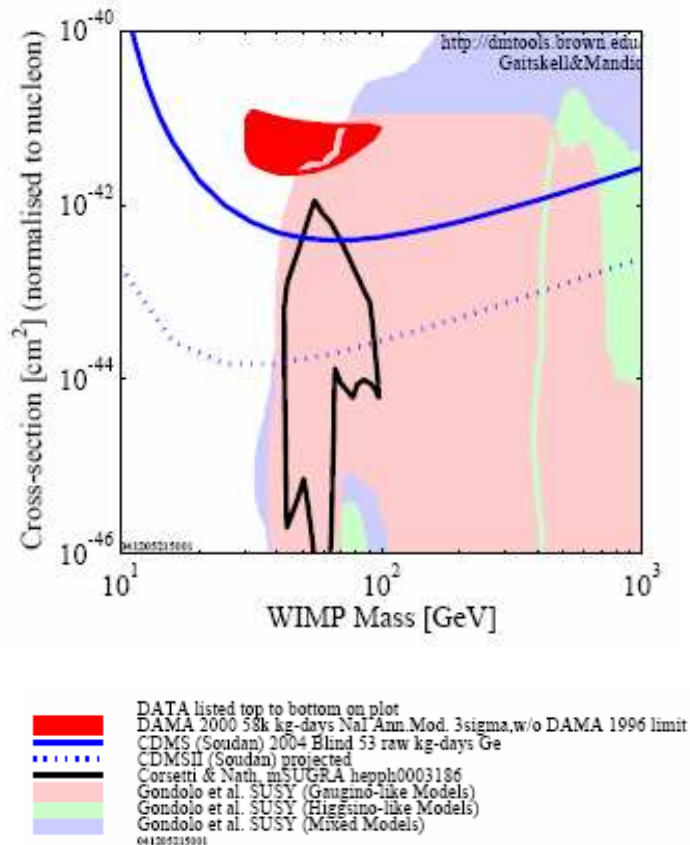
- In the S-model, $\tan\beta$ is only (1 – 3) which gives only negligible coupling of $Z\text{-}\chi\text{-}\chi$ for the MSSM. (irrelevant channel in the MSSM)
- Because of the modified mass and coupling of the LSP (χ^0_1), the $Z\text{-}\chi\text{-}\chi$ coupling is enhanced even for small $\tan\beta$. (opening of new channel)



Barger, Kao, Langacker, HL
PLB600 (2004) 104]

- The S-model [multiple singlet $U(1)'$ model] has a broad range of parameter space that reproduces the acceptable CDM relic density even in the limit of large Z' -ino mass. (More general parameter scan is [in preparation].)

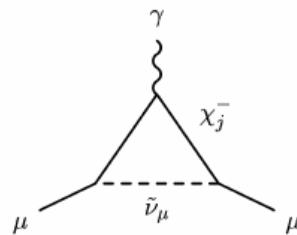
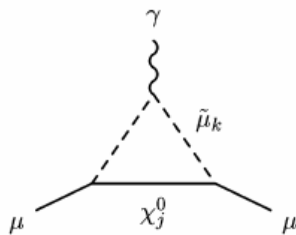
(ii) Direct CDM detection



- The cross-section of nuclear recoil of dark matter will be different from the MSSM (because of altered mass and coupling of both Higgs and neutralino).
- Direct neutralino detection may discover a SUSY particle (neutralino) even before LHC.

(iii) Muon anomalous magnetic moment $(g-2)_\mu$

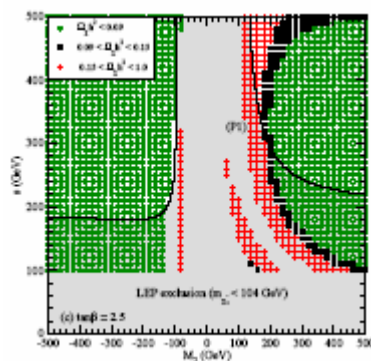
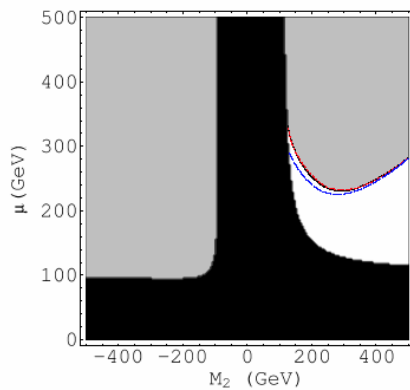
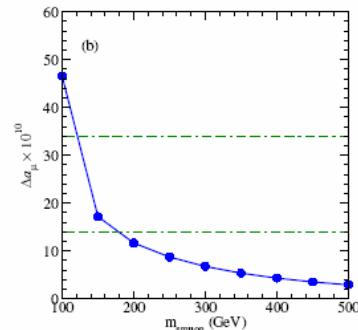
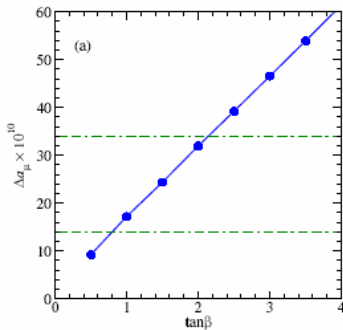
- $(g-2)_\mu$ is one of the most precisely measured quantities.
- 2.4σ deviation from SM prediction (0.9σ if hadron information is from indirect hadronic τ decay)
- New physics at TeV-scale could give significant contribution to $(g-2)_\mu$:
 - In MSSM, $\text{sign}(\mu) > 0$, upper limits on slepton masses
 - Mass of second generation leptoquark
 - Mass of heavy photon (γ') in Little Higgs model
 - Compactification scale in an extra dimension
 - Z' mass in $U(1)'$ or GUT models (if only Z' -loop is considered)
 - Split SUSY would be rejected (if deviation is true).



$$\Delta a_\mu(\text{SUSY}) \sim 13 \times 10^{-10} \frac{\tan \beta \operatorname{sign}(\mu)}{(M_{\text{SUSY}}/100 \text{ GeV})^2}$$

- neutralino-smuon and chargino-sneutrino loop contributions in supersymmetric models

- Same supersymmetric contribution to $(g-2)_\mu$ but with an extended neutralino sector.
- In the S-model, $\tan\beta$ is small. \rightarrow Can it still explain $(g-2)_\mu$ deviation?




Barger, Kao, Langacker, HL [Preliminary]

- Even with small $\tan\beta$, S-model can explain the $(g-2)_\mu$ deviation while satisfying all LEP constraints on chargino mass, smuon mass.
- The deviation constrains smuon mass to be less than 180 GeV. \rightarrow easily detectable at LHC or ILC (of moderate 500 GeV).
- Further, there is a *common area* that can explain both $(g-2)_\mu$ and CDM relic density simultaneously.

(4) Gauge boson sector

- Gauge boson sector (Z') :
It may affect Z boson through Z - Z' mixing. If Z' coupling is family non-universal, FCNC (Flavor Changing Neutral Current) by Z' occurs at the tree-level.
- (Besides the detection of Z' and mixing of Z - Z'), flavor-changing Z' would have important implications on
 - (i) B-factory ($B_d \rightarrow \phi K_S, B_d \rightarrow \pi K$)
 - (ii) Tevatron or LHC ($B_s \rightarrow \mu^+ \mu^-$)
 - (iii) EW Precision Test ($A_{FB}^{0,b}$)

- 
- The Z' contribution is suppressed by its large mass, but its effect is tree-level.
 - FCNC in SM are all loop-suppressed.
 - Expect sizable FCNC by flavor-changing Z' .

- $U(1)'$ coupling matrix in interaction eigenstate (d_L^{int}):

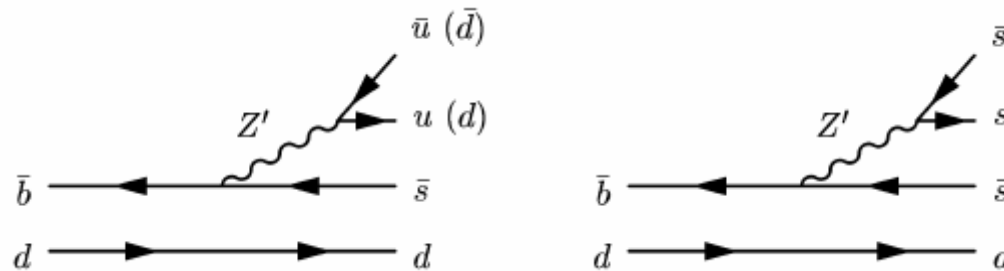
$$\epsilon_{d_L} = Q_{d_L} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 + \delta \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- $U(1)'$ coupling matrix in mass eigenstate ($d_L = V_{d_L} d_L^{\text{int}}$):

$$\begin{aligned} B^L &\equiv V_{d_L} \epsilon_{d_L} V_{d_L}^\dagger = Q_{d_L} V_{d_L} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 + \delta \end{pmatrix} V_{d_L}^\dagger \\ &= \begin{cases} Q_{d_L} \mathbf{1}_{3 \times 3} & (\text{if } \delta = 0) \\ \text{general } 3 \times 3 \text{ matrix} & (\text{if } \delta \neq 0) \end{cases} \end{aligned}$$

(i) Implications on B-factory (BaBar, Belle) experiments


- Some of new data from B-factories do not agree with the SM predictions.
- $B \rightarrow \phi K_S$ CP asymmetry ($S_{\phi K}$) was deviated by 3.5σ in Belle experiment. (It has been one of the hottest issues since 2002.)
- $B \rightarrow \pi K$ branching ratios showed 2.4σ deviation from the SM (by separate BaBar, Belle, CLEO data). And it suggests NP effect in EW Penguin sector.
- *The deviations are reduced in 2004 data, but the data still show the discrepancies.*



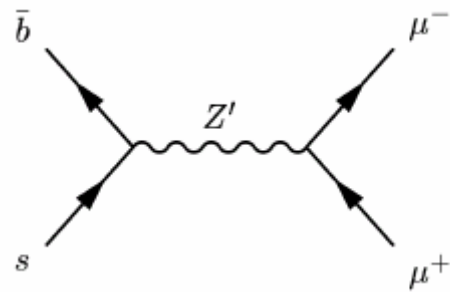
Barger,Chiang,Langacker,HL [PLB580 (2004) 186]

Barger,Chiang,Langacker,HL [PLB598 (2004) 218]

- Both $B \rightarrow \phi K_S$ and $B \rightarrow \pi K$ anomalies can be successfully explained with a flavor-changing Z' with *common* parameter values.

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- Flavor-changing Z' solution is one of the few solutions that can explain both anomalies in $B \rightarrow \phi K_S$ and $B \rightarrow \pi K$ with the same parameter values without conflicts with related experiments such as $B \rightarrow \eta' K_S$ and Mercury EDM(Electric Dipole Moment).

(ii) Implications of Tevatron (or LHC) experiments



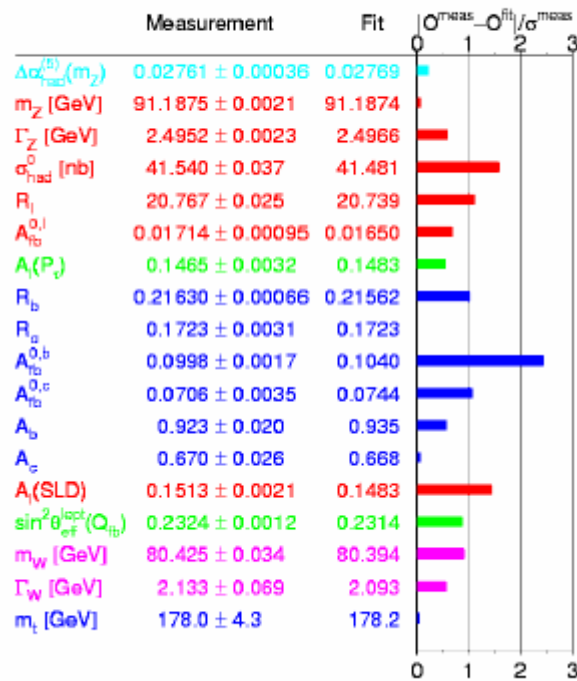
- Flavor-changing Z' models predict $B_s \rightarrow \mu^+\mu^-$ production may be large enough to be observed at Tevatron Run2.

Barger, Chiang, Langacker, HL [hep-ph/0310073]

(iii) EW Precision Test

EWWG

Summer 2004



Good agreement with SM predictions !

Largest discrepancy:
 $A_{FB}^{0,b}$

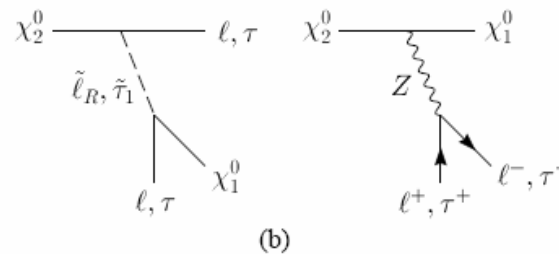
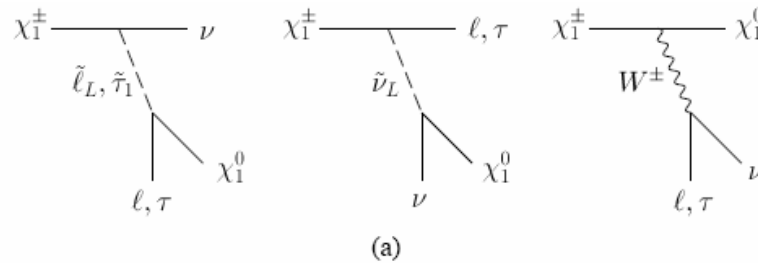
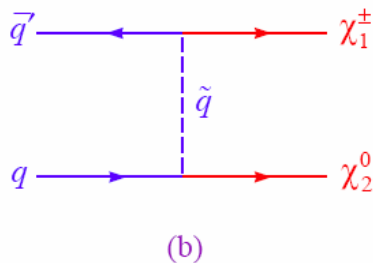
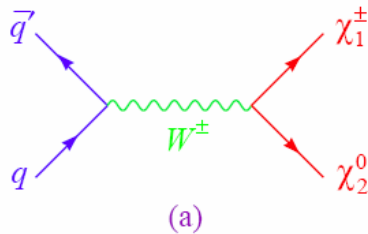
- EWPT agrees well with SM.
- The largest discrepancy (2.5σ) of $A_{FB}^{0,b}$ may be due to flavor-changing Z' .

Rieman [Workshop on Z's (Nov '04)]


Erler, Langacker [PDG review 2004]

(iv) Trilepton signal from chargino-neutralino associated production


$$q\bar{q}' \rightarrow \chi_1^\pm \chi_2^0$$





- Trileptons from chargino-neutralino associated production is altered in $U(1)'$ -MSSM. [in preparation]



5. Summary and Outlooks

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- SM was extended to the MSSM to resolve the fine-tuning problem (gauge hierarchy problem), but the MSSM has its own fine-tuning problem (μ -problem) related to Higgs mixing parameter.
 - NMSSM can cure it with a discrete symmetry and a Higgs singlet, but causes another problem (domain wall problem). [cf. nMSSM]
 - $U(1)'$ -extended MSSM may be a natural extension of the MSSM : It solves the μ -problem elegantly and is rationalized by many new physics models that predict additional $U(1)$ symmetries. [GUT, Extra dim, String, Strong dynamics, Little Higgs, Stueckelberg, ...]

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- Solution of μ -problem implies EW/TeV-scale for the $U(1)'$ gauge boson Z' .
 - CDF Run2 currently constrains to $M_{Z'}$ to be larger than $500 \sim 800$ GeV; LHC can search up to 5 TeV.
 - Particle spectrums are extended in the $U(1)'$ -extended MSSM [Gauge boson, Higgs, Neutralino, Neutrino] and properties of “important” particles [light Higgs, lightest neutralino (LSP)] may change.

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- Not only because of Z' itself, but also because of modified mass and couplings of MSSM particles, the phenomenological implications are rich :
 - High-E collider physics [Higgs, trilepton, ...]
 - B-physics [$B_d \rightarrow \phi K_S$, $B_d \rightarrow \pi K$, $B_s \rightarrow \mu^+ \mu^-$, ...]
 - Non-collider [$0\nu\beta\beta$, $(g-2)_\mu$, ...]
 - Astro/Cosmology [BBN, CDM relic density, EWBG, ...]
 - EWPT [$A_{\text{FB}}^{0,b}$, ...]
 - The most important thing is observing the resonance in Tevatron/LHC and identifying the source of it.

For more about $U(1)'$ -extended MSSM

- For more details and references for the $U(1)'$ -MSSM or Z' , please visit my website :

The Z' Hunter's Guide

<http://pheno.physics.wisc.edu/~comety/hunter/>

(maintained to be kept up-to-date)

- You can also try “ Z' Hunter's Guide” at .